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EXPERIMENTS WITH PLANING SURFACES

By W. Sottorf

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 661

EXPERIMENTS WITH PLANING SURFACES*

By W. Sottorf

67th Report of the Hamburg Naval Tank (H.S.V.A.)

Experiments with planing surfaces are fundamental hydrodynamic researches for the purpose of obtaining the most favorable forms for planing boats, flying boats, and seaplane floats, with respect to water resistance and seaworthiness.

I. TESTS OF MODELS OF PLANING AND FLYING BOATS
AND THEIR ANALYSIS

Figure 1 shows typical water-resistance curves for a planing boat and a flying boat.

The planing boat has a resistance curve which, because of the constant weight of the boat, shows a continually increasing resistance with increasing speed. The resistance increases approximately quadratically up to the instant of the beginning of planing, and in the planing condition increases with a power less than 2.

The flying boat is lightened by the wing lift which increases as the square of the speed. The resistance curve therefore first reaches a maximum value and then falls off to reach zero at the instant of take-off; that is, when the wing lift equals the gross weight. The flying boat can take off with any load for which the sum of the water and air resistances remains less than the propeller thrust.

*Expanded treatment of a paper read before the principal meeting of the Gesellschaft der Freunde und Förderer der Hamburgischen Schiffbau-Versuchsanstalt G.m.b.H., May 25, 1929. From author's reprint of article in "Werft-Reederei-Hafen," Nov. 7, 1929, pp. 425-432.

Three classes of models may be used in this work:

1) Massive wood or paraffin models. These usually are three to five times as heavy as the weight corresponding to their scale. The excess weight must be balanced by a weight suspended over a sheave R. (Fig. 2.) The mass forces from oscillations in the direction of motion, which affect the resistance measurements, are therefore three to five times those of a model having true mass similarity. Those from vertical oscillations are five to nine times as great. Consequently, to obtain unaffected measurements,

2) Weight-similar models are generally used. Their weight inclusive of the balance weight is G/λ^3 .

3) Dynamically similar models are used, especially for tests in waves, in order to give a true reproduction of the motion of the full size in pitching. Their model weight is G/λ^3 and their mass moment of inertia T/λ^5 ; where G = weight and T = mass moment of inertia of the full scale, and λ = model scale.

Figure 2 shows the test arrangement A. The weight-similar model is balanced about the c.g. of the whole aircraft and suspended at the c.g. by means of a fork. The wing lift is produced by a weight suspended over sheave R. The model is towed in the propeller thrust line by a wire bridle, which leads forward to the resistance dynamometer and aft to a small tension weight. Two guides forward and aft of the model hold it in the direction of motion. The resistance is measured by means of a spring, while the rise and the trim angle are read on corresponding scales.

The fundamental tests are runs made according to Froude's law, with the model free to trim, at various constant speeds over the speed range up to take-off. The wing lift is supplied by the balance weights and is corrected during the runs according to the angle of attack of the wings as determined from the trim angle.

However, with this method of towing it is not possible to study two problems which require dynamic similarity of the masses in motion and massless lift:

1) The testing of a float in acceleration corresponding to the true starting regime (take-off). This would be

very desirable in order to study its motions, since from experience, almost every float, beyond the hump, i.e., at the start of planing, has a tendency to pitch. Too much importance is given to this pitching in tests made at constant speed, since then it naturally persists throughout the run and gives poor readings. In fact, when taking off the aircraft quickly passes through the critical range and shortly thereafter begins to plane, which results in smooth running.

An additional advantage of this method of testing would be that the whole of the resistance curve referred to above, together with the accelerating forces, would be obtained in one run.

2) The testing of a float in a seaway, both at constant speed and while being accelerated. This presents the same requirements.

The first problem can be studied in the circular tank of the Junkers Company. The model is towed in a circular channel, suspended and guided by a hinged arm whose vertical axis lies at the center of the channel. If the suspension point on the axis lies above the attachment point on the model, then the vertical component of the centripetal force, which increases as the square of the r.p.m., is applied to the model. By changing the height of the suspension point on the axis any wing lift can be obtained.

The apparatus of the H.S.V.A. for towing dynamically similar models in a straight towing tank consists of a combination of the resistance body developed at the tank for use on trial trips with the float test apparatus. Since the resistance body has a water resistance increasing exactly as the square of the speed, it is only necessary to connect the pull of the resistance body to the suspension wire of the float by a suitable linkage, arrangement B, Figure 3. A lever and quadrant are interposed and make it possible to vary the point of attachment of the pull from the resistance body. The lift corresponding to get-away speed can be obtained by suitably locating the point where the pull is applied to the lever. The resistance body is a rather light cone, and the force required to accelerate it is so small in comparison to the total force that it can be neglected, so that at each moment of the run the correct wing lift is applied.

A further development of the gear is proposed in which the slider to which the pulling wire of the resistance body is attached will be moved by a motor controlled by the model itself in such a manner as to produce the lift corresponding to the exact angle of attack of the wings.

The resistance body properly should lie off to one side of the model so that any influence on the model may be avoided.

American tests for the same purpose in which a hydrofoil was arranged in the water under the model to give the corresponding lift led, among other things, to errors due to interference with the model.

Full information on the model is given only by tests at different constant trim angles, since the resistance is dependent on the trim angle and a further important resistance effect appears which is dependent on the trim angle and is produced by the water flowing under the step and wetting the afterbody.

By moving a sliding weight (fig. 2) the necessary moment is applied to the model during the run to maintain the desired angle of trim.

It is the task of the airplane designer to construct the float or boat so that as far as possible it will give the most favorable angle of attack for the wings of the airplane and so that the control surfaces can apply the proper moments, in order that the get-away may take place at the most favorable angle of attack for the particular speed range.

The economy of the flying boat is increased by lowering the maximum resistance. This gives an increase in the useful load, which means an increase in fuel capacity or an increase in range. With it is also obtained a shorter time of take-off, much desired on account of the heavy structural loads while taking off in a seaway. By making changes in the planing bottom, changes in the position and height of the steps, changes in the afterbody with regard to the spray, or by the construction of a new boat with different principal dimensions, etc., it is possible by simple comparison to determine the relatively most favorable model.

Figure 4 shows the comparison of systematic tests of a flying boat with five different bottoms. There are important differences in the resistances of the individual designs. Bottom form No. 1, for instance, has two conditions of maximum resistance; traveling in smooth water the water does not break away from the step with the result that the resistance steadily rises. Unsticking can be accomplished by jarring the model. The model then rises on the step and the resistance falls to the lower branch of the curve. In practice this boat would be able to get off only in rough water.

This method of developing a type is still followed generally. The tests nevertheless remain unsatisfactory because they are derived from a form which, lacking previous fundamental knowledge, has been developed by the designer principally by feeling or instinct, and a variation of all the design elements which have a bearing on the problem must be neglected, primarily because of the great length of time required for the tests and the correspondingly high costs. Consequently the information which is obtained regarding the effects of changes is often deceptive; e.g., a change in the bottom form of the forebody might be favorable of itself but because the afterbody is not suitable for use with it an apparent failure might be obtained because of the effects of the spray.

A recognition of this fact led the firm of Rohrbach to conduct at the Hamburg tank the first systematic tests with different bottom forms of forebody alone. The afterbody was separated by a vertical cut at the step, while the load remained equal to the total load. In these tests the great increase in resistance due to the wake running back along the afterbody appeared plainly. For instance, the combination of one of the completely investigated forebodies with a certain afterbody gave a 30 per cent increase in resistance because the afterbody, although of itself out of the water, was wetted for its entire length by a stream of water coming out from under the step. A suitable deflecting device reduced the resistance to almost that of the forebody alone.

Models of similar type but with different loadings and get-away speeds are compared according to Figure 5. In this the ordinates are the planing numbers $\epsilon = W/A$, where W is the resistance, A the dynamic lift, and the

abscissas are $\frac{v}{v_0}$ = speed ratio = $\frac{\text{observed speed of model}}{\text{take-off speed of model}}$.

By making numerous tests with seaplane models of similar loading and the same scale, it is probably possible to determine empirically an envelope for the numerous curves which would represent the curve for the best model.

However, the question of how near we are to the theoretically best model is still unsolved. The test results from work done for different private concerns must be treated as confidential, consequently material for comparison is restricted.

II. SYSTEMATIC TESTS WITH PLANING SURFACES

As early as 1924 tests with box-shaped bodies were undertaken at the Hamburg tank by Dipl. Eng. M. Popp as a basis for planing boat construction, in order to determine the planing number for flat and V-bottom forms and for different trim angles and loads. These experiments could not be carried out to the proposed extent because of lack of funds.

About a year and a half ago the test program which is described in more detail later on was set up because of the pressing necessity for a basis for analyzing flying boats. The first results of this program are presented here.

The following considerations lead immediately to the choice of a plane rectangular plate for the fundamental investigations, as being the planing surface with presumably the best planing number.

Tangential and normal forces act on the under side of a plate which is moving through a fluid at rest while the upper side remains under constant atmospheric pressure. It is assumed that the water flows away freely from the bounding edges of the bottom surface.

In the case of a frictionless fluid the tangential or friction forces equal zero. From Figure 6a it is seen that the resultant of the normal force N for trim angle α gives $W = A \tan \alpha$ as a minimum resistance.

From Figure 6b it is seen that, assuming the addition of the friction force T , the resistance becomes

$W = A \tan \alpha + \frac{T}{\cos \alpha}$, as, in accordance with the conditions of the tests, the lift A is assumed to be constant.

If one considers the cross section of a V-bottom plate with plane inclined surfaces and assumes for simplicity that the trim angle is small and may be neglected, the normal force on one side, according to Figure 6c is $\frac{N}{2} =$

$$\frac{A/2}{\sin \left(\frac{\beta}{2} \right)} \quad \text{or} \quad N = \frac{A}{\sin \left(\frac{\beta}{2} \right)}. \quad \text{For the flat plate } \sin \left(\frac{\beta}{2} \right) = 1,$$

hence $N = A$. With increasing deadrise, N and the lost component N_v both increase, as well as the wetted surface, if the constant lift A is maintained, as a result of which the total resistance of the V-bottom, and also of the curved bottom, exceeds that of the flat plate.

The Test Program

The systematic study of the plates was conducted as follows:

1) For a given plate, the influence of trim angle α on planing number $\epsilon = W/A$ was determined by towing at constant speed and load, but with each test run at a different trimming moment.

2) The effect of increasing load was determined by repeating the first tests at higher loadings.

3) The effect of increasing speed was found by repeating the first group of tests at higher speeds. It was assumed that the lift increased as the square of the speed.

4) After the relations for one plate were known, tests were made for comparison with one or two other series of tests, in order to determine the effect of varying breadth of plate (variation of aspect ratio) by towing relatively wider plates at constant loads and constant speeds.

5) The conversion of the model results to full size by Froude's method showed good agreement almost to the maximum resistance, however, as the size of the models was reduced an increasing discrepancy appeared, as Hermann and Kloss pointed out as a result of tests with models at

various scales carried out at the H.S.V.A. (Fig. 7.) Although up to the maximum resistance the hydro- and aerodynamic lifts are small, and consequently there is no difference between a flying boat, a planing boat, and a displacement boat, thereafter, with increased hydrodynamic lift, the planing condition is reached, and it is necessary to obtain a conversion formula of the form $W = w \lambda^3 - f(\lambda)$. The first term expresses the conversion of the total resistance measured as form resistance, according to Froude's law, while the second expresses the difference in friction, according to Reynolds law, as a correction for "Scale Effect." By testing plates of different widths, as outlined above under (4), the law of conversion for the planing condition can be found. The scales of the models are derived from the relations of the plate widths to each other. On the basis of Froude's law the tests were conducted at corresponding speeds and loads and the results used to determine the second term of the conversion formula.

This method has the advantage over tests with actual hull models in that the effects of spray which would cause the results to lose their general validity, are avoided.

6) In the same way the influence of different bottom forms, deadrise, curvature, etc., are to be determined by comparative tests, in which, in place of flat plates test floats are used with the same over-all dimensions but with different bottom forms.

Apparatus

Preliminary tests were run with a flat glass plate to determine the forms of the wetted surfaces. In the apparatus described hereafter, the angle of attack and the length below the still water level were determined by reading the change of draft (fore and aft) from the zero reading (plate level on the water surface). The impact pressure of the water on the plate increases the true wetted surface. By looking through the glass plate the wetted length is easily determined by reading the impact water line on a scale on the plate. For a plate having a width of 0.3 meter the dynamic water line is a flat arc of about 10 mm midordinate for all speeds, angles, and loads. Accordingly, it was permissible in the succeeding experiments to use an aluminum plate about 6 mm thick, in

which a glass plate 50 mm wide had been fitted at the quarter point. A mean value of the wetted length was read through this small glass plate.

The plate was pin-jointed to two vertical rods, each of which was guided at both top and bottom of its guide frame by three ball-bearing rollers. (Fig. 8.) The guide frames were supported at their c.g. axis on knife-edges. Their weight was supported from the carriage while the rods formed a part of the load on the plate. At the level of the axis of each guide frame a steel wire was secured to a short cross member on the guide rod. The counterweights were attached to these wires and suspended over sheaves R_1 and R_2 . The loading weights were placed on scalepans on the guide rods. By changing the loading weights or counterweights any desired loading of the plate could be obtained, while by shifting the loading weights or counterweights from one rod to the other any moment could be obtained. Rise and trim angle were determined by graphical record of the change of rise of each guide rod on a drum.

The resistance dynamometer consists of an equal armed lever supported freely on two knife-edges. A coarse balance weight and the tension of a spring, which is varied by an electric motor controlled by two contacts, hold the resistance in balance. The extension of the spring registers on a drum so that an accurate mean resistance is obtained. The time and travel of the carriage are registered at the same time to determine its speed. By this arrangement the weighing lever, and hence the forward guide rod are maintained in the vertical position. The slight angularity of the after guide rod at large angles of trim is taken care of by a correction.

The Test Procedure

When the carriage is not in motion ring stops on the guide rods hold the plate so that the leading edge is above water. During the accelerating run the plate gradually assumes, of itself, the depth corresponding to the predetermined load and the angle of attack corresponding to the predetermined moment, so that on reaching constant speed measurements can be taken.

Tests on the .3m Wide Flat Plate

The loads and speeds chosen appear in the following table. The load is increased as the square of the speed, and accordingly the load coefficient $C_B = \frac{A}{\frac{\rho}{2} b^2 v^2}$ remains constant.

Loading case	Load coefficient $C_B = \frac{A}{\frac{\rho}{2} b^2 v^2}$	Speed in meters per second			
I	0.25 × 0.218	4 kg	9 kg	16 kg	22.6 kg
II	0.5 × 0.218	8 "	18 "	32 "	45.2 "
III	0.75 × 0.218	12 "	27 "	48 "	-
IV	1.0 × 0.218	16 "	36 "	-	-

Run No.	Angle of attack α°	Wetted length l in mm (fig.14)	Length below the water surface l in mm (fig.14)	Resistance W in g	Moment M in mkg about trailing edge	Moment coefficient $\frac{M}{A b C_B}$	$\frac{l_p}{l^2}$ (fig.14)
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Speed $v = 4$ m/s, Loading case I; $A = 4$ kg

	deg.	min.						
1	1	11	770	715	820	1.925	29.40	0.701
2	2	12	465	415	610	1.419	21.65	0.761
3	2	43	325	275	490	1.052	16.05	0.806
4	4	3	160	113	450	0.522	7.98	0.812
5	5	26	100	60	475	0.403	6.16	0.820
6	6	34	85	50	550	0.373	5.72	0.841
7	7	21	70	42	550	0.326	4.99	0.852
8	9	8	60	36	660	0.283	4.33	0.860
9	10	59	45	25	770	0.232	3.54	0.890

Run No.	Angle of attack α°	Wetted length l' in mm (fig.14)	Length below the water surface l in mm (fig.14)	Resistance W in g	Moment M in mkg about trailing edge	Moment coefficient $\frac{M}{A b C_p}$	$\frac{l_p}{l'}$ (fig.14)
Speed $v = 4$ m/s, Loading case II; $A = 8$ kg							
	deg.min.						
10	2 57	765	695	1070	3.821	14.60	0.637
11	3 1	748	675	1140	3.835	14.70	0.635
12	4 13	545	472	1105	3.112	11.90	0.708
13	5 25	395	330	1100	2.423	9.28	0.741
14	6 34	278	216	1130	1.714	6.56	0.761
15	7 31	215	155	1180	1.387	5.31	0.798
16	7 58	195	140	1220	1.244	4.76	0.788
17	9 3	170	110	1360	1.076	4.12	0.717
18	11 18	140	84	1600	0.847	3.24	0.730
Speed $v = 4$ m/s, Loading case III; $A = 12$ kg							
19	4 3	855	760	1630	6.212	10.55	0.601
20	5 1	705	610	1645	5.512	9.36	0.646
21	6 7	585	491	1710	4.828	8.20	0.682
22	7 8	495	406	1805	4.159	7.08	0.693
23	8 5	395	305	1980	3.460	5.88	0.729
24	9 22	320	234	2150	2.832	4.82	0.726
25	10 54	255	171	2360	2.578	4.39	0.740
Speed $v = 4$ m/s, Loading case IV; $A = 16$ kg							
26	5 6	910	792	2260	8.640	8.26	0.587
27	6 7	785	662	2420	7.971	7.61	0.627
28	7 49	615	499	2625	6.609	6.31	0.662
29	9 31	475	359	2920	5.249	5.02	0.679
30	10 54	385	270	3240	4.315	4.12	0.686
Speed $v = 6$ m/s, Loading case I; $A = 9$ kg							
31	2 22	710	655	1710	4.863	32.90	0.754
32	3 1	490	433	1410	3.406	23.10	0.709
33	4 8	240	188	1105	1.964	13.30	0.788
34	4 37	220	174	1050	1.458	9.90	0.805
35	4 45	177	130	1020	1.245	8.45	0.787
36	5 10	150	104	1100	1.036	7.02	0.788

Run No.	Angle of attack α°	Wetted length l' in mm (fig.14)	Length below the water surface l in mm (fig.14)	Resistance W in kg	Moment M in mkg about trailing edge	Moment coefficient $\frac{M}{A b C_B}$	$\frac{l_p}{l'}$ (fig.14)
Speed $v = 6$ m/s, Loading case I; $A = 9$ kg							
	deg.min.						
37	5 49	108	66	1125	0.840	5.70	0.856
38	6 57	95	58	1210	0.733	4.97	0.848
39	7 47	82	44	1300	0.603	4.09	0.883
40	8 35	62	30	1380	0.562	3.81	0.946
41	9 53	56	28	1575	0.497	3.37	0.973
Speed $v = 6$ m/s, Loading case II; $A = 18$ kg							
42	2 36	1400	1325	3320	14.350	24.40	0.633
43	3 47	915	838	2880	11.587	19.70	0.697
44	4 10	810	739	2820	10.866	18.45	0.704
45	4 15	780	705	2770	9.930	16.90	0.729
46	5 8	580	507	2595	6.329	10.78	0.748
47	5 31	515	448	2630	7.063	12.00	0.752
48	5 40	490	420	2630	6.561	11.17	0.760
49	6 53	318	250	2710	4.518	7.67	0.767
50	7 54	235	168	2870	3.080	5.23	0.785
51	8 58	182	117	3050	2.431	4.13	0.740
52	9 34	163	101	3170	2.181	3.72	0.733
Speed $v = 6$ m/s, Loading case III; $A = 27$ kg							
53	2 41	1695	1590	4700	26.370	19.95	0.570
54	3 34	1310	1205	4320	22.609	17.07	0.632
55	4 22	1095	994	4130	20.060	15.15	0.674
56	5 13	937	832	4120	17.531	13.22	0.683
57	5 26	873	716	4140	16.478	12.45	0.691
58	6 24	682	587	4230	13.661	10.32	0.709
59	6 43	640	545	4280	13.142	9.93	0.717
60	7 25	538	442	4360	10.834	8.19	0.728
61	8 3	478	380	4540	9.438	7.13	0.726
62	9 12	390	287	4770	7.391	5.58	0.728
63	9 48	346	252	4950	6.697	5.06	0.709

Run No.	Angle of attack α°	Wetted length l' in mm (fig.14)	Length below the water surface l in mm (fig.14)	Resistance W in kg	Moment M in mkg about trailing edge	Moment coefficient $\frac{M}{A b C_B}$	$\frac{l_p}{l'}$ (fig.14)
Speed $v = 6$ m/s, Loading case IV; $A = 36$ kg							
	deg.min.						
64	3 52	1565	1435	5870	33.380	14.18	0.581
65	4 19	1385	1255	5790	30.750	13.08	0.612
66	5 6	1200	1075	5690	28.350	12.00	0.650
67	5 35	1120	993	5670	26.510	11.25	0.650
68	6 16	985	860	5720	24.680	10.50	0.688
69	6 43	943	820	5960	22.710	9.63	0.674
70	6 57	923	800	6010	22.724	9.63	0.674
71	7 43	745	624	6250	19.521	8.26	0.681
72	8 11	690	564	6300	18.020	7.63	0.678
73	8 46	623	498	6490	16.052	6.81	0.704
74	9 30	509	386	6760	13.368	5.67	0.712
75	10 8	463	343	7010	11.883	5.05	0.702
Speed $v = 8$ m/s, Loading case I; $A = 16$ kg							
76	2 32	810	750	3130	10.187	38.90	0.779
77	2 42	620	565	2900	9.011	30.60	0.801
78	3 24	401	340	2260	5.093	19.45	0.810
79	3 43	275	217	2060	3.638	13.90	0.821
80	4 35	178	118	1820	2.200	8.42	0.781
81	5 0	143	88	1750	1.848	7.06	0.802
82	5 13	145	94	1860	1.859	7.10	0.796
83	5 51	125	78	1930	1.534	6.05	0.827
84	6 57	88	43	2180	1.217	4.66	0.837
85	7 57	65	20	2470	1.076	4.11	0.830
86	9 12	72	38	2690	1.019	3.89	0.870
Speed $v = 8$ m/s, Loading case II; $A = 32$ kg							
87	4 21	792	709	5150	19.092	18.25	0.746
88	5 3	640	560	4870	15.508	14.83	0.760
89	5 31	507	425	4780	12.639	12.08	0.774
90	6 19	350	275	4760	8.348	7.98	0.796
91	6 57	306	236	4760	7.294	6.97	0.764
92	7 20	258	185	4910	6.302	6.02	0.752

Run No.	Angle of attack α°	Wetted length l' in mm (fig.14)	Length below the water surface l in mm (fig.14)	Resistance W in kg	Moment M in mkg about trailing edge	Moment coefficient $\frac{M}{A b C_B}$	$\frac{l_p}{l'}$ (fig.14)
Speed $v = 8$ m/s, Loading case II; $A = 32$ kg							
	deg.min.						
93	7 20	248	179	4950	6.307	6.02	0.760
94	7 39	238	168	4980	6.336	6.02	0.750
95	7 57	202	130	5070	5.270	5.04	0.751
96	8 26	190	120	5230	4.623	4.42	0.748
97	9 40	150	82	5580	3.676	3.51	0.753
Speed $v = 8$ m/s, Loading case III; $A = 48$ kg							
98	6 38	738	632	7880	26.017	11.05	0.726
99	6 59	625	521	7980	22.479	9.55	0.741
100	7 10	627	523	7920	22.483	9.55	0.738
101	8 11	468	365	8220	16.810	7.20	0.738
102	8 25	430	329	8370	14.008	5.94	0.737
Speed $v = 9.5$ m/s, Loading case I; $A = 22.6$ kg							
103	2 50	680	610	4160	12.167	32.90	0.790
104	3 10	422	357	3530	8.135	22.00	0.820
105	3 52	296	233	2790	5.199	14.06	0.802
106	4 45	199	134	2600	3.801	10.30	0.813
107	5 13	170	110	2660	3.104	8.39	0.801
108	6 20	110	54	2910	2.039	5.52	0.813
109	7 24	80	28	3120	1.263	3.41	0.693
Speed $v = 9.5$ m/s, Loading case II; $A = 45.2$ kg							
110	4 29	820	735	6980	28.015	18.98	0.749
111	5 7	628	545	6730	22.319	15.11	0.765
112	5 50	490	407	6680	16.550	11.22	0.763
113	6 42	315	232	6800	10.864	7.36	0.754
114	7 44	242	168	7070	8.146	5.52	0.736

In Figure 9 are entered:

1. The measured resistances less the air drag determined by towing the horizontal plate just above the water.

2. The curves of form resistance $W_F = A \tan \alpha$.

3. The curves of frictional resistance W_R , computed according to Prandtl's friction formula for a turbulent boundary layer with laminar approach.

$$W_R = \frac{\rho}{2} v_m^2 F c_f$$

in which $\rho = \text{density} \frac{\gamma}{g}$

$v_m = \text{mean velocity of the water relative to the plate}$

$F = \text{measured wetted surface} = l' b$

$l' = \text{wetted length}$

$$c_f = 0.073 \left(\frac{1}{R} \right)^{0.2} - \frac{1600}{R}$$

$$R = \text{Reynolds Number} = \frac{vl}{\nu}$$

4. The curves $(W_F + W_R)$

5. The mean reduction in speed of the water relative to the plate $v_u = v - v_m$ in per cent of the towing speed v , as determined by pressure measurements.

A complete agreement of the measured values with the curves $(W_F + W_R)$ appears at lower loads, while with increasing loads at small angles of attack an increasing difference appears. This difference is explained in part by the gradual appearance at small angles of attack of spilling over the edge, and in part by the increasing effect of the edges on the establishing of the boundary layer and consequently on the coefficient of friction c_f with increasing ratio of l'/b .

Figure 10 presents the curves of planing number $\epsilon = W/A$ against angle of attack α . Both upper parts of the

diagram show the change of planing number with increasing speed at constant load coefficient for loadings I and II. A notable variation is apparent only for $v = 4$ m.p.s. at small angles, where a condition of laminar boundary layer predominates.

The lower part of the diagram gives the planing numbers determined for the higher velocities for the four cases of loading I to IV. At large angles of attack with decreasing friction W_F , the curve of resistance W approaches the curve of form resistance $W_F = A \tan \alpha$ asymptotically, from which the planing number, $\tan \alpha$, is derived as the asymptote. The minimum planing number lies between 4° and 6° . Toward smaller angles the planing number increases with the rapidly increasing wetted surface. Toward larger angles the planing number increases rapidly with the form resistance as a function of $\tan \alpha$. The lowest value is 0.114, the resistance is therefore about $1/9$ the lift. Further tests with lower loads are proposed for the determination of the curve of optimum planing numbers.

The results indicate that with increasing load, as a result of the greater wetted length in relation to the breadth, the planing number becomes worse.

The Pressure and Velocity Distribution on the Plate

For the study of the pressure distribution the plates were fitted with 85 holes of 2 mm diameter. These were fitted on one side only, at the center line, at the quarter beam, and at 4 mm from the edge, as well as at a number of intermediate points. From each hole a connecting tube led to a glass manometer tube secured on a panel at right angles to the plate. The tubes were connected together at the upper ends by a cross tube, by which the water in the connecting tubes could be sucked up simultaneously and colored. For each test the plate was secured to the two guide rods in the proper position to give the desired load and angle of attack. When constant speed was reached, air was allowed to enter the cross tube, so that the water in each tube stood at the height corresponding to the pressure, and could be photographed or marked.

The pressure distribution was investigated for $v = 6$

m.p.s. and $A = 18$ kg for 4° , 6° , and 8° angle of attack. (Fig. 11.)

At the leading edge of the wetted surface, where impact and change in direction of the water occurs, the pressure rises immediately to a maximum, and quickly drops off. At small angles it reaches zero at the trailing edge. Toward the sides it falls off only a little compared to the pressure at the center line. At the sides the water escapes as a jet on account of the sudden pressure drop. From the trailing edge the water continues on in the direction given by the plate until a jet shoots up from the rebound of the water displaced by the plate. This jet is the principal cause of the great increase of resistance in flying boats when the water touches a poorly formed afterbody.

From the pressure distribution it is deduced that, for instance, at 4° , the mean pressure, with respect to the whole wetted surface, is smaller than with a wider plate with the same load where the after part of the pressure range is missing. But if the wider plate has the greater mean pressure the wetted surface, and consequently the friction and total resistance, is smaller. Tests with plates of various widths should clear up this question experimentally.

Bernoulli's equation makes it possible to determine the velocity distribution on the plate from the pressure distribution, as shown in Figure 11. The mean velocity along the plate length is also plotted against the plate width, from which as the mean of the velocity cross section, the speed v_m is obtained as an average speed over the entire plate. For the computation of the frictional resistance W_R , the mean reduction in speed $v_u = v - v_m$ as a per cent of the towing speed v , is shown in Figure 9 as a function of the trim angle α .

Separation of the Resistances

The total resistance is first divided into frictional resistance W_R , and form resistance W_F . This last is to be divided into the induced resistance W_i , analogous to the induced resistance in the wing theory, and the wave resistance W_w , which is due to the motion of a body moving in a boundary between two media. As W_R is readily determined with

sufficient exactness, we obtain W_w after determining W_i .

According to the law of momentum the newly created momentum per second or the momentum $\rho F' v w$ is equal to the lift A . In this $\rho = \gamma/g$ = density, F' is the cross section of the mass affected, v is the horizontal speed of the plate, and w is the downward velocity of the mass considered. For simplicity let a rectangular section F' be assumed over the width b of the plate, which because of the relatively small reduction of pressure toward the side appears permissible. Further, let there be introduced for the determination of the downward velocity w the average velocity w_m over the entire plate, then $w_m = v_m \sin \alpha$. If one calls the mean height of the affected mass h_m then we have

$$\rho h_m b v w_m = A \quad (1)$$

The kinetic energy created per second is equal to the work of the induced resistance; that is,

$$\rho h_m b v \frac{w_m^2}{2} = W_i v$$

from which

$$W_i = \frac{A^2}{2 \rho v^2 h_m b} \quad (2)$$

According to equation (1) h_m and W_i are determined for the three cases investigated, as

	4°	6°	8°
h_m	0.238 m	0.162 m	0.126 m
W_i	0.617 kg	0.906 kg	1.16 kg

Figure 12 shows the constituent parts of the separate resistances, which at the minimum resistance form approximately equal parts of the total. In contrast to the wing theory the share of the frictional resistance in the total resistance is great, and on account of the unknown wetted length l' it cannot be determined theoretically with accuracy; on the other hand, there enters also a notably large

wave-making resistance which can be determined mathematically only by the expenditure of very much time, so that only systematic research can produce the necessary bases for the predetermination of the resistance, moment, and angle of attack of any gliding body.

Figure 13 shows the moment coefficient $C_m = \frac{M}{A b C_p}$ plotted against α . The moment is referred to the trailing edge of the plate. With increasing speeds the moment curve for a single loading condition approaches a boundary curve which corresponds approximately to the curve for $v = 9.5$ m/s. At large angles the curves approach a common asymptote. The introduction of the wetted length l' instead of C_m gives a group of curves of the same character. The separation of the curves is therefore determined by the changing of the pressures with a power not equal to 2, and yet greater than 2 at low speeds, which falls to 2 at the boundary curve. For this reason the predetermined lift, which varies as the square, is reached at a shorter wetted length at the lower speeds. Further tests are planned for the confirmation of these first results.

In Figure 14 the position of the center of pressure is plotted as l_p/l' in which l_p is the distance of the center of pressure from the after edge and l' is the wetted length. All the points of the same loading case fall on the same slightly curved line, that is the ratio of l_p/l' is approximately constant. With increasing load the value of l_p/l' decreases.

On the basis of results so far, since the intensity of loading corresponds approximately to that of the flying boat, Figure 4, a minimum line can be drawn in that figure which shows that with the best designs, where more value is attached to low resistance than to the best sea-going qualities, the minimum resistance of the flat plate is still exceeded by 20 to 40 per cent.

The most important result of these tests to date may be said to be that it is possible to make comparisons between the later tests of the program and one or two series of suitably related tests, which will give the work a practical application.

SUMMARY

After an introduction regarding the performance and evaluation of tests of flying boats, the first results of tests with flat planing surfaces are described, which form the basis for further systematic tests to be made with flat plates and vee-bottom forms.

Translation by
The Staff, N.A.C.A. Tank.

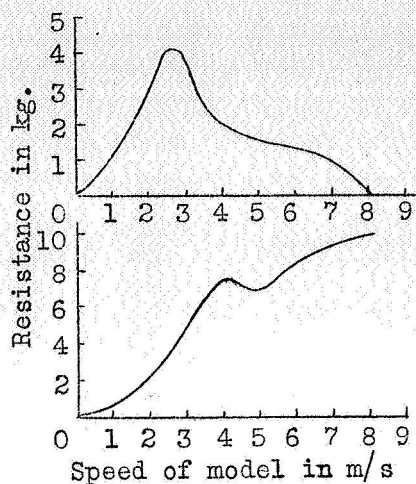
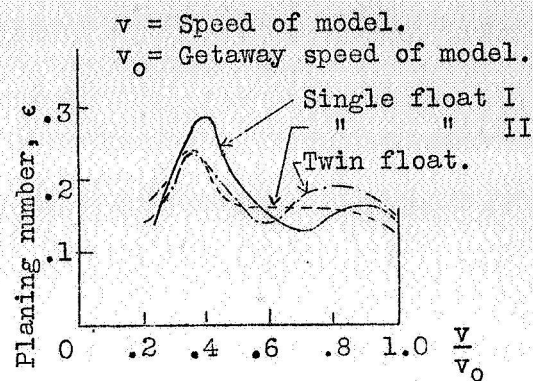


Fig. 1 Resistance curve of a planing boat with a displacement of 58 kg (below) and of a flying boat with a displacement of 18 kg (above).



$$\text{Planing number } \epsilon = \frac{W}{G - T}$$

W = Resistance
G = Weight of aircraft
T = Lift from wings

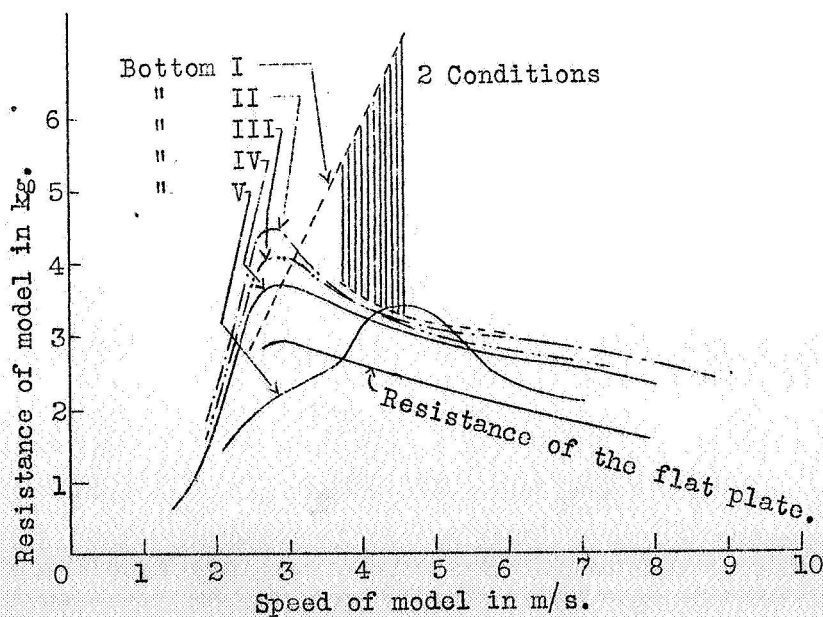


Fig. 4 Resistances of flying boat with five different forms of bottom. Displacement = 18 kg.

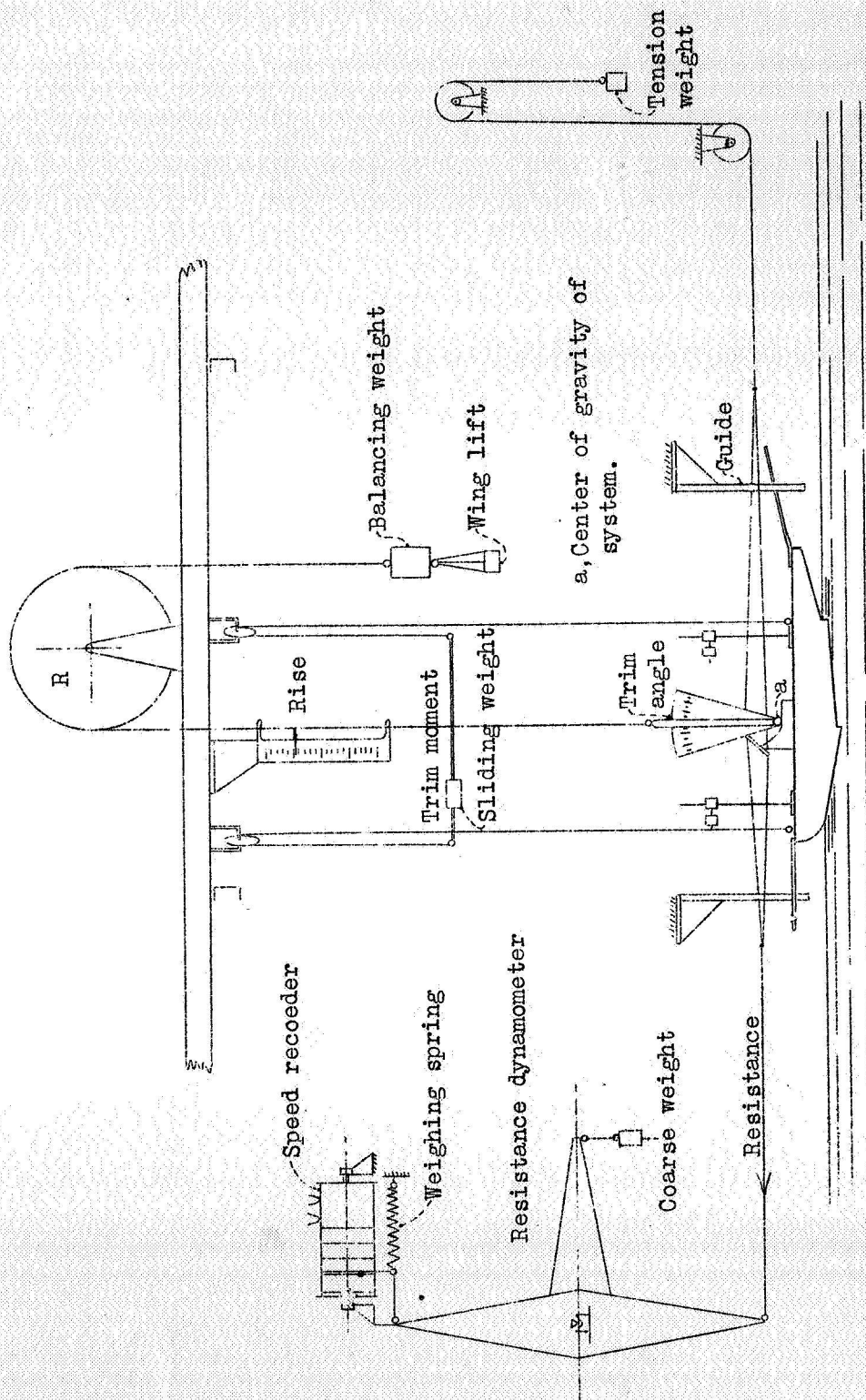


Fig.2 Diagram showing test arrangement A for flying boats.

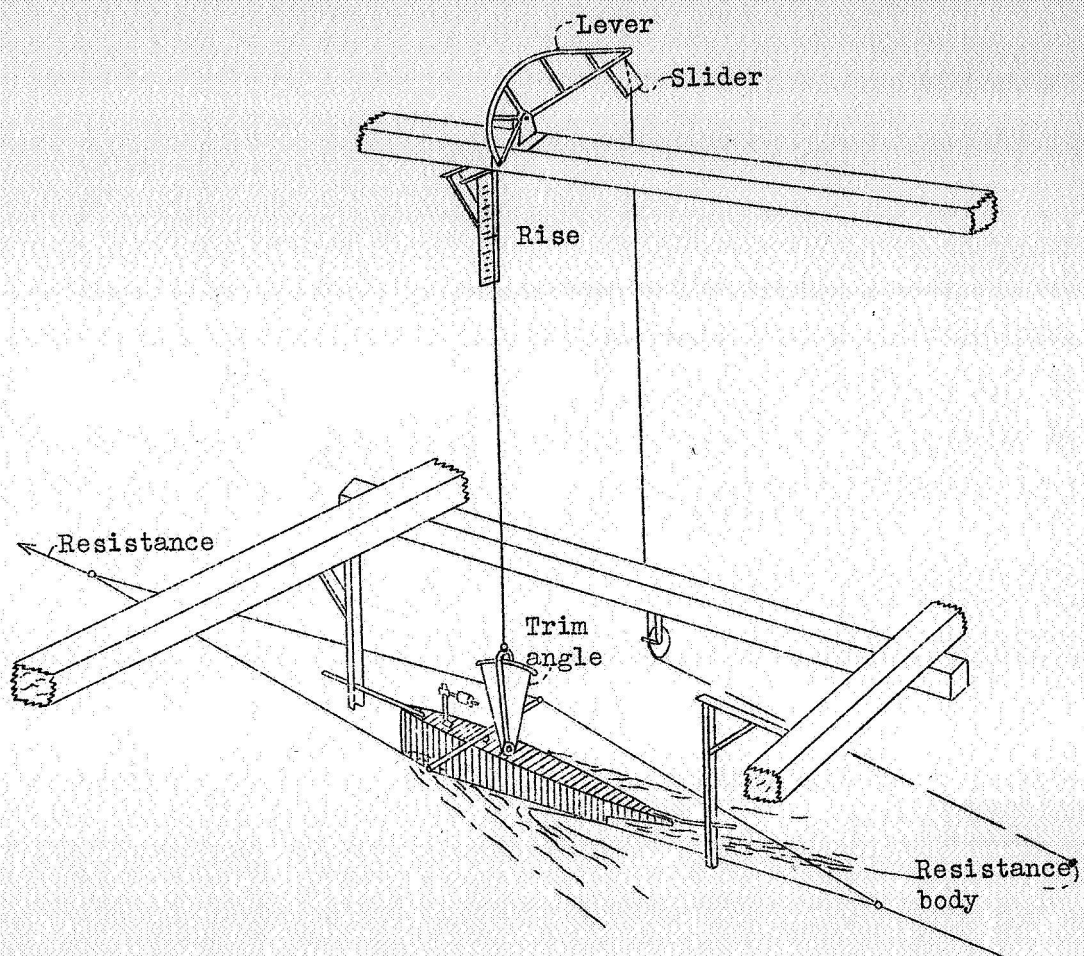


Fig.3 Diagram showing test arrangement B for towing dynamically similar models.

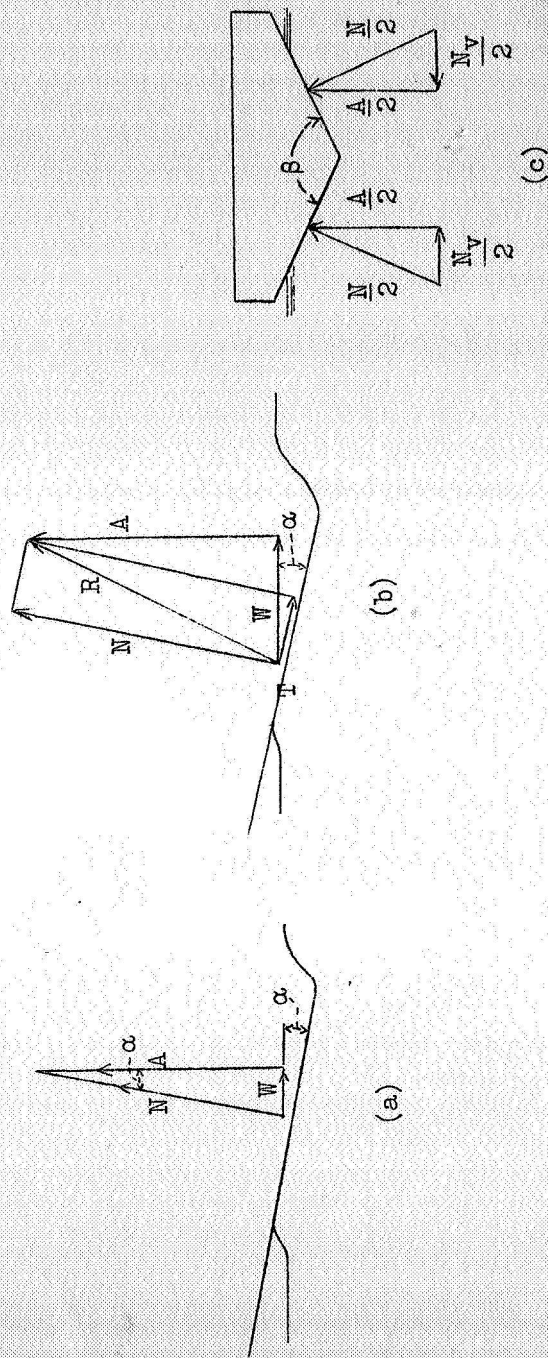


Fig.6 (a) Forces on the flat plate in a frictionless fluid.
 (b) " " " " " viscous fluid.
 (c) " " " " " with deadrise at small angles of trim.

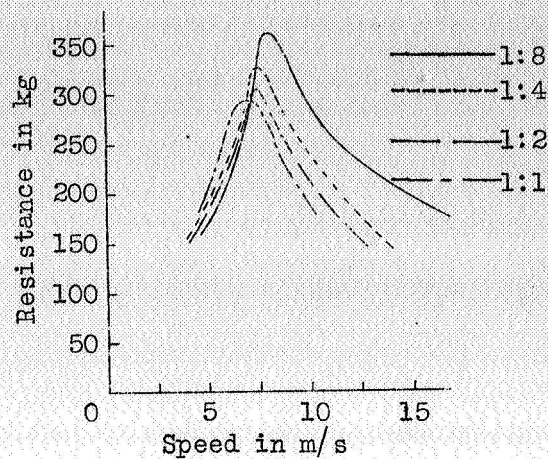


Fig.7 Resistances of similar floats tested at scales of 1:1, 1:2, 1:4,,and 1:8, converted to the resistance of a float having a displacement of one ton.

o, Load case IV; $c_B = 1 \times 0.218$ g, Load case II; $c_B = 0.5 \times 0.218$
 f, " " III; $c_B = 0.75 \times 0.218$ h, " " I; $c_B = 0.25 \times 0.218$

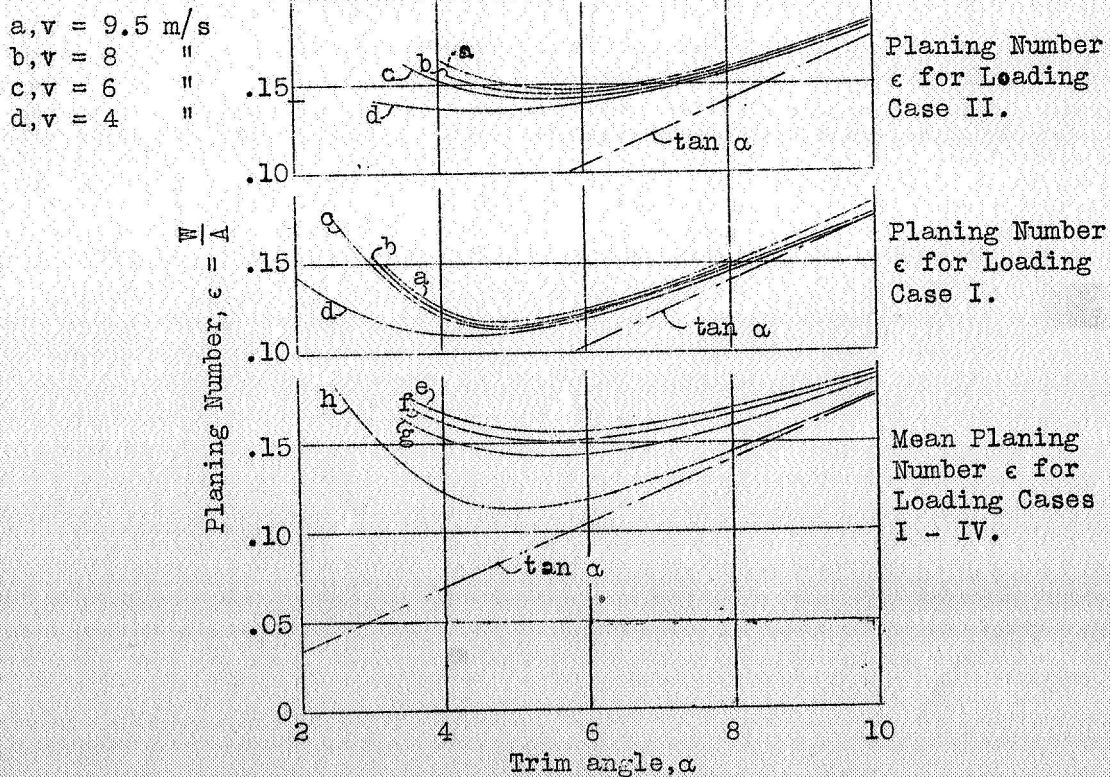


Fig.10 Curves of the Planing Numbers, $\epsilon = \frac{W}{A}$.

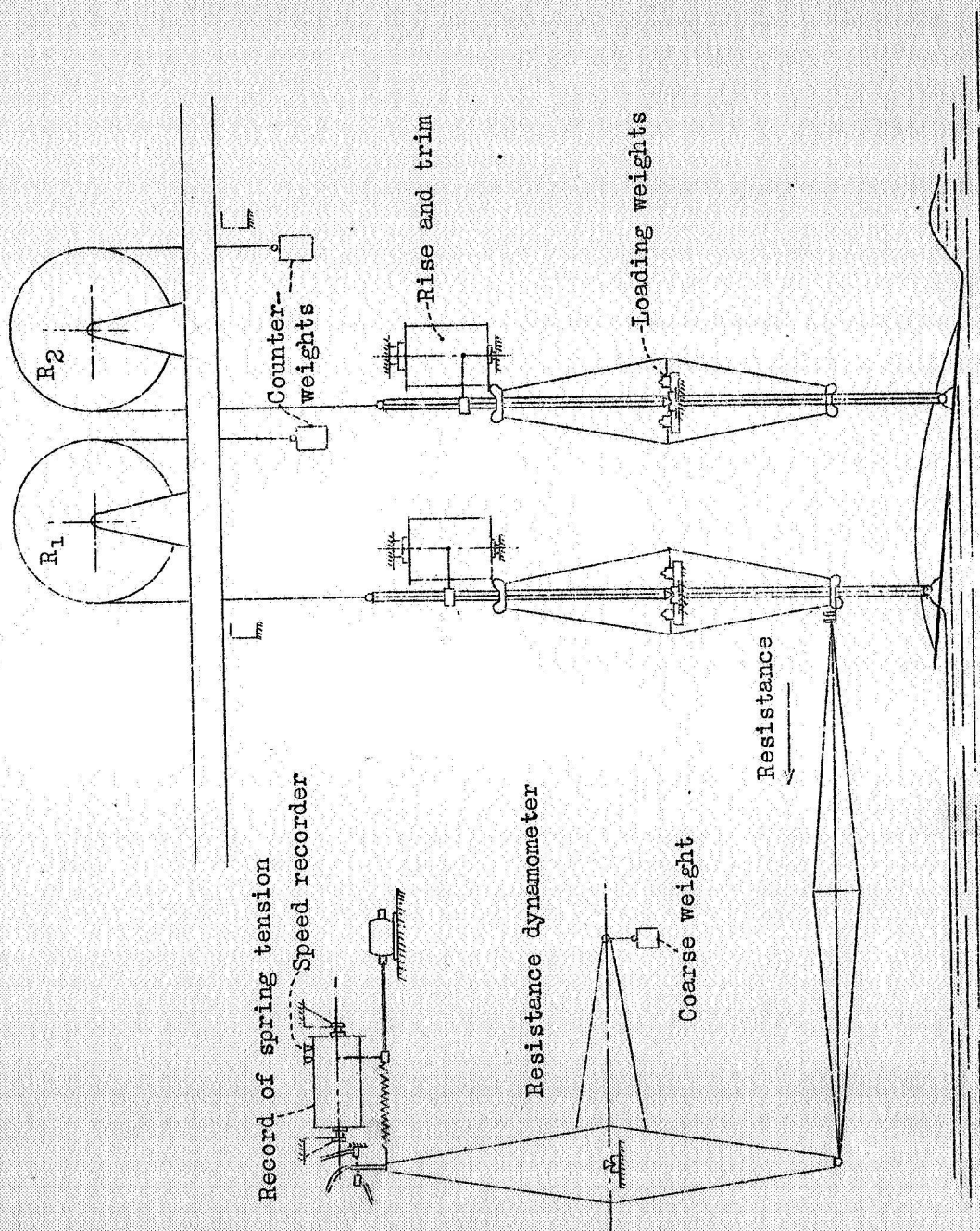


Fig.8 Diagram showing the arrangement used in tests of planing surfaces.

$$C_f = 0.073 \left(\frac{1}{R} \right)^{0.2} \frac{1600}{R}$$

F = Area of wetted surface.
 v_m = Mean speed over surface.

Form resistance $W_F = A \tan \alpha$
 Frictional resistance $W_R = \frac{C_f}{2} v_m^2 F$

Measured resistances

- a, A = 16 kg
- b, A = 12 "
- c, A = 8 "
- d, A = 4 "
- e, A = 36 kg
- f, A = 27 "
- g, A = 18 "
- h, A = 9 "

Mean reduction in speed over the surface $v_u = v - v_m$ in per cent of the towing speed, v

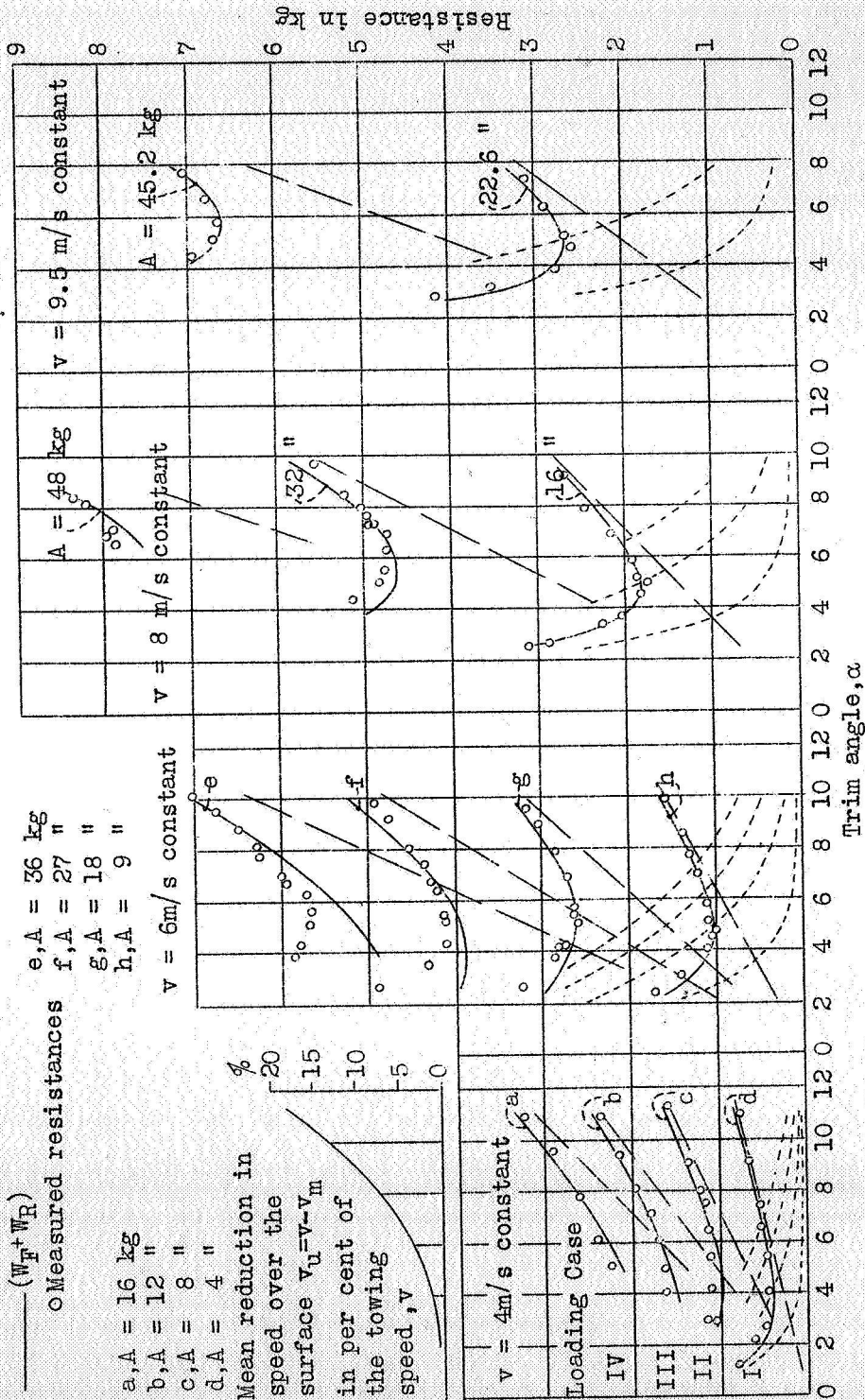


Fig. 9 Resistance of the 0.3 in wide flat planing surface, referred to trim angle α .

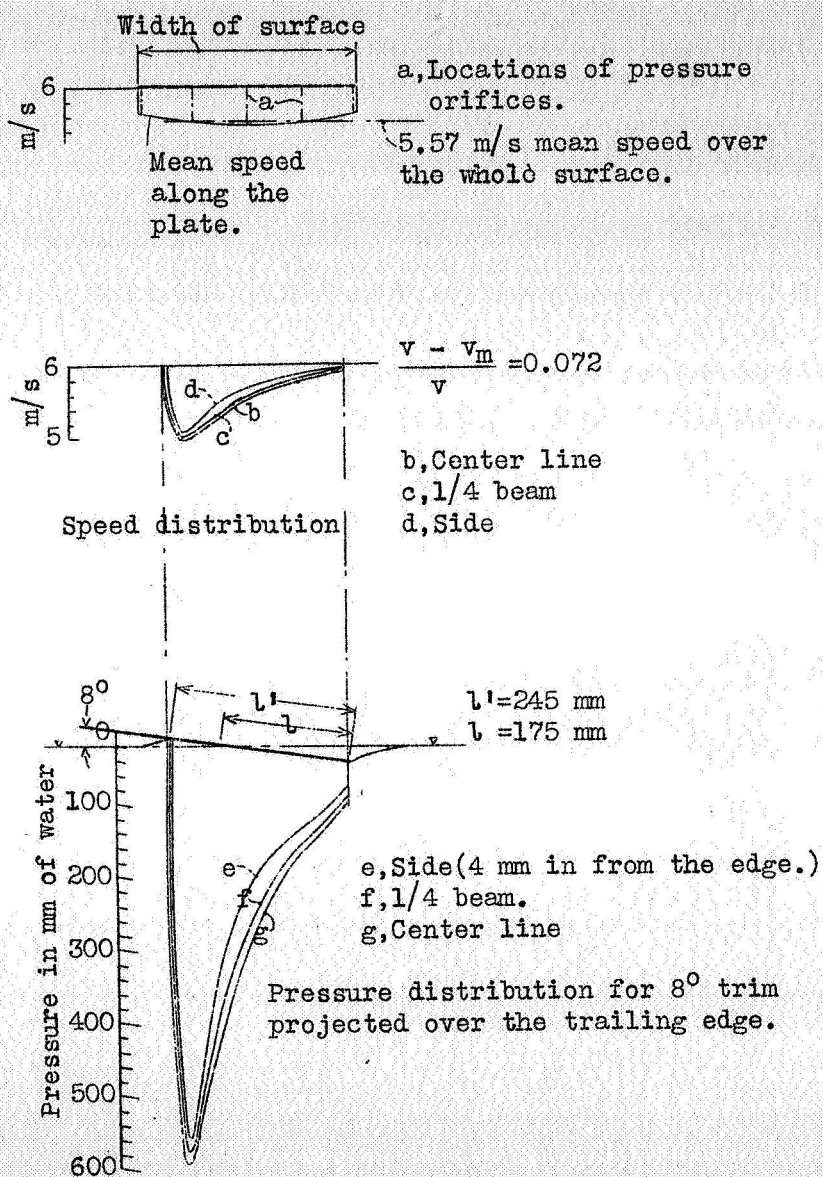
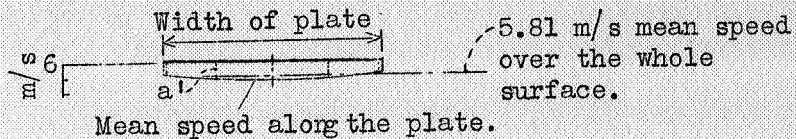
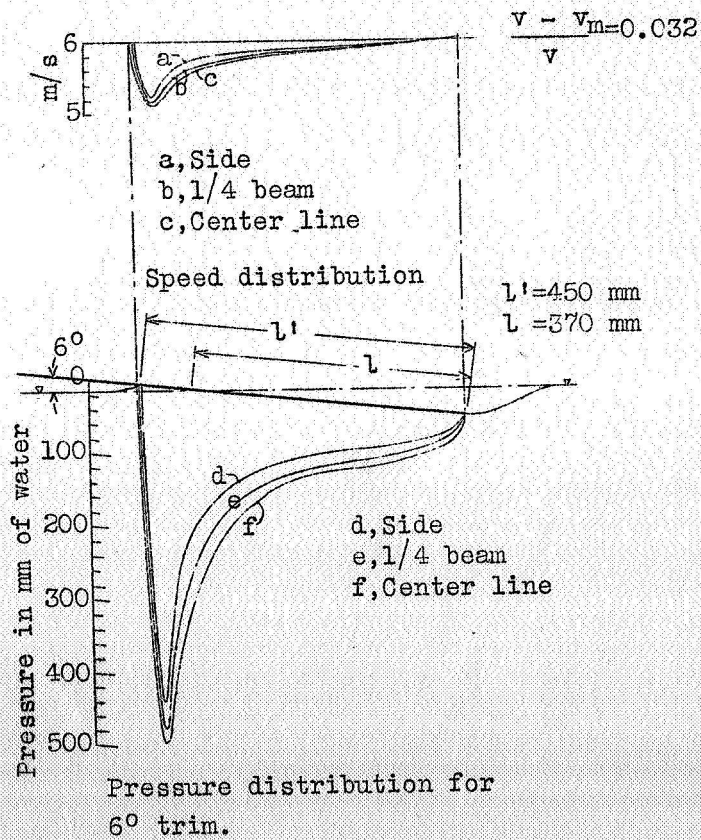


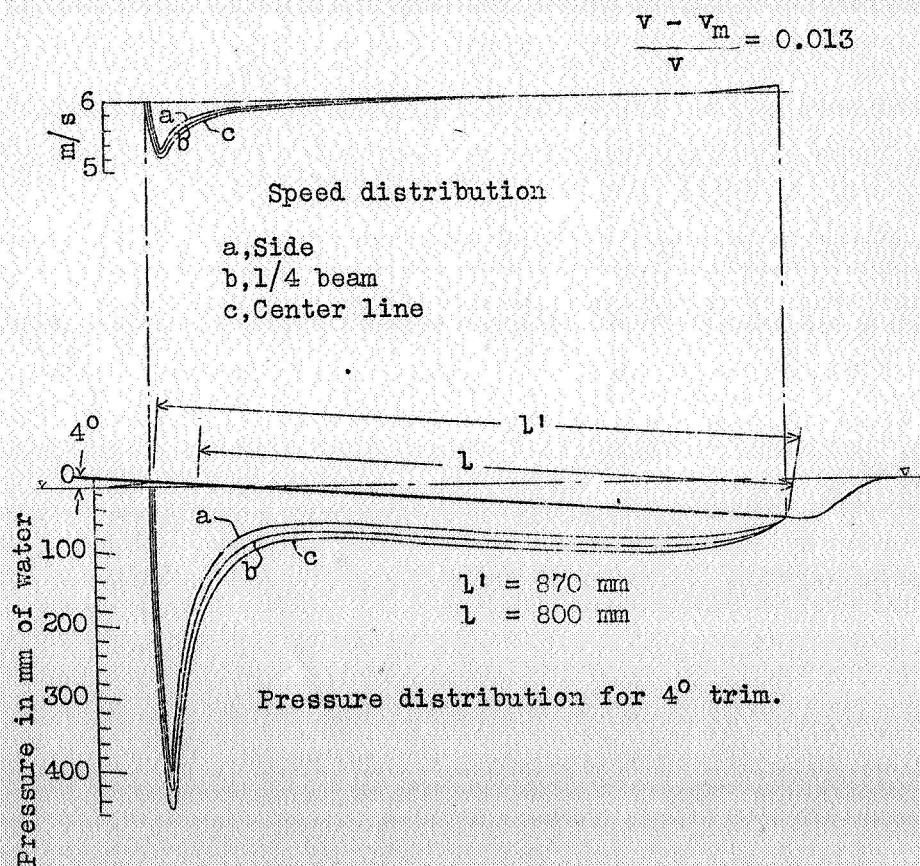
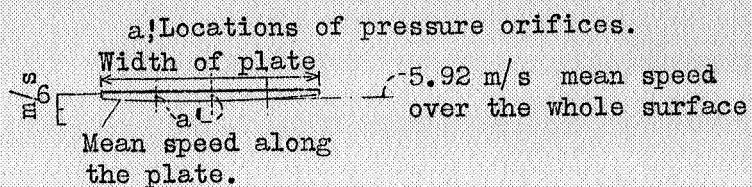
Fig.11 Speed and pressure distribution over a wide flat Planing surface. Speed of towing, $v = 6$ m/s Load, $A = 18$ kg
(Continued on next two pages)



a', Locations of pressure orifices.



(Continuation of Fig.11)



(Conclusion of Fig.11)

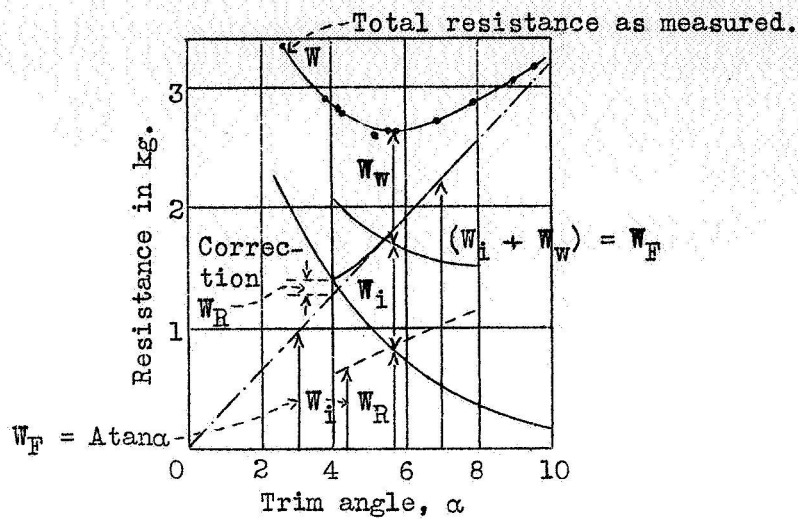


Fig. 12 Division of the resistance for $v = 6$ m/s and $A = 18$ kg.

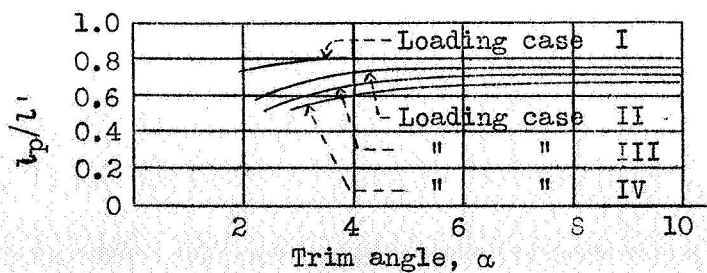
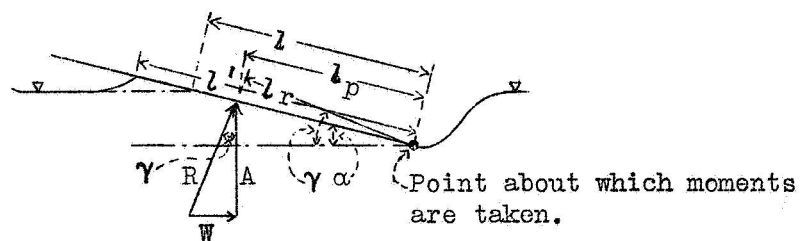


Fig. 14 Postition of the center of pressure.

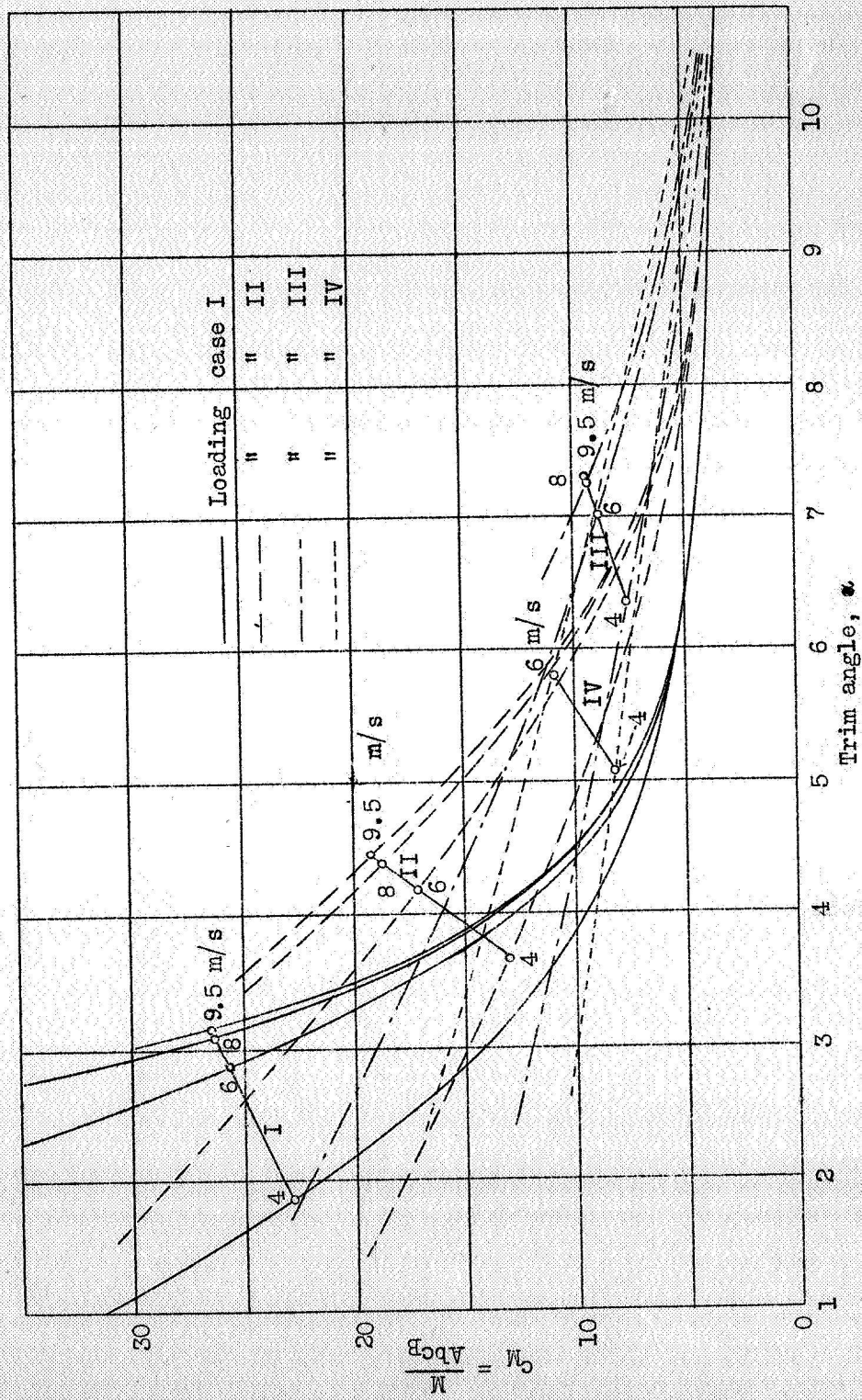


Fig. 13 Moment coefficient c_M against trim angle α .